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Mixing Dynamics of Supercritical Droplets and Jets

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14. ABSTRACT

This report summarizes a research program to understand the mixing dynamics of supercritical droplets and jets. The research was motivated by the recognition that pressures in modern liquid rocket engine combustion chambers tend to be higher than the critical pressure of one or more of the propellants. Prior to the beginning of this research, combustion processes were largely modeled using low pressure, subcritical spray combustion concepts. At supercritical pressures, however, a distinct difference between "gaseous" and "liquid" phases no longer exists, surface tension and the enthalpy of vaporization vanish, and "gas" phase density can approach that of the "liquid" with correspondingly significantly enhanced aerodynamic forces relative to the "liquid." These and other effects are discussed in detail in the references contained in the report. Under such conditions, questions such as whether droplets can even exist or what "spray combustion" would look like lacked even qualitative answers at the beginning. As a result of the research conducted under this program, most of the qualitative questions have now been answered, and significant progress has been made in determining quantitative mechanisms.

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NOTICE

FOREWORD

This final report, entitled "Mixing Dynamics of Supercritical Droplets and Jets," presents the results of a research study performed under JON 2308M13C by AFRL/PRSA, Edwards AFB CA. The Project Manager for the Air Force Research Laboratory was Dr. Douglas G. Talley.

This report has been reviewed and is approved for release and distribution in accordance with the distribution statement on the cover and on the SF Form 298.

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EXECUTIVE SUMMARY

This report summarizes a research program to understand the mixing dynamics of supercritical droplets and jets. The research was motivated by the recognition that pressures in modern liquid rocket engine combustion chambers tend to be higher than the critical pressure of one or more of the propellants. Prior to the beginning of this research, combustion processes were largely modeled using low pressure, subcritical spray combustion concepts. At supercritical pressures, however, a distinct difference between "gaseous" and "liquid" phases no longer exists. Surface tension and the enthalpy of vaporization vanish, and "gas" phase density can approach that of the "liquid," with corresponding significantly enhanced aerodynamic forces relative to the "liquid." These and other effects are discussed in detail in the references listed below. Under such conditions, questions such as whether droplets can even exist or what "spray combustion" would look like lacked even qualitative answers at the beginning. As a result of the research conducted under this program, most of the qualitative questions have now been answered, and significant progress has been made in determining quantitative mechanisms.

Early work consisted of studying cryogenic liquid oxygen (LOX) droplet behavior at subcritical and supercritical pressures [1-11]. This included a considerable effort to learn how to produce droplets at supercritical pressures. Shadowgraph and spontaneous Raman scattering measurements showed that the classical low-pressure sequence of primary atomization, secondary breakup, and vaporization is not accurate at supercritical pressures. Due to the lack of surface tension, droplets at supercritical pressures instead continuously deform while simultaneously vaporizing.

Initial work on single jets (as opposed to droplets) at various pressures also took place during this initial period. Visualizations of nearly laminar liquid nitrogen (LN2) jets clearly demonstrated that surface tension becomes vanishingly small as the critical pressure is approached, even while density gradients remain large enough to make the LN2/ambient gas interface look smooth and glassy [6]. This work also showed that adding helium to the ambient gas could cause surface tension to clearly reappear even at pressures above the critical pressure of N2, due to mixture effects.

Research then turned to the behavior of simple, round, turbulent jets at various pressures ranging from subcritical to supercritical [12-23]. It was found that at subcritical pressures, the jets had a classical spray appearance, but that as pressure was increased past the critical pressure, the jets assumed an appearance of gaseous jets with no evidence of droplets. The initial divergence angle indicating the growth rate of the jet was measured using shadowgraphy at the jet exit. These values were then compared with those measured from a large number of other mixing layer flows, including atomized liquid sprays, turbulent incompressible gaseous jets, supersonic jets, and incompressible but variable density jets covering over four orders of magnitude of the gas-to-liquid density ratio. This was the first time such a plot had been reported for such a large range of density ratios. At and above the critical pressure, it was found that the growth rate measurements agreed well with both theory and measurements for incompressible, variable density, gaseous mixing layers. At subcritical pressures, the growth rate measurements were consistent with those reported for classical sprays. A physics-based mechanism was postulated and used to correlate the data over the entire four-decade range of density ratios. Spreading rate measurements of the supercritical jets were also made using spontaneous

Raman scattering. Raman measurements of subcritical jets were found not to be useful due to broadband emissions caused by focusing of the laser illumination by the jets. The Raman measurements were found to be consistent with the shadowgraph measurements if twice the full-width-half-maximum normalized intensity measurements were used. Finally, measurements of the fractal dimension of the shadowgraph images were performed. These provided further evidence of the gas-like behavior of the supercritical jets. The fractal dimension of the supercritical jets was consistent with the fractal dimension reported by others for gaseous jets; while the fractal dimension of the subcritical jets was consistent with the fractal dimension reported by others for classical sprays. Some of these results could be compared with similar work being reported out of Germany. The results of the two independent laboratories were found to corroborate each other [23-24].

Steady-state studies of simple round jets were followed by studies of acoustically driven round jets [25-26]. The jets were driven transversely by acoustic drivers specially designed for operation at high pressures. In all cases, the jets tended to flatten in the mean, with the long dimension perpendicular to the direction of the acoustic waves. This could be explained by the lower pressures around the shoulders of the jet caused by the higher velocities there through the Bernoulli effect. The magnitude of the effect, however, was found to depend strongly on the pressure. The magnitude of the effect was strong at subcritical pressures, strongest near the critical pressure, but weak at supercritical pressures. The implications of these results regarding liquid rocket combustion instabilities were considered. It was concluded that coupling mechanisms for supercritical jets were likely to be very different from those for subcritical jets, and that insufficient attention had been paid to supercritical effects in past studies of liquid rocket combustion instabilities.

Simple round jet results were then extended to coaxial jets, where the central condensed jet is surrounded by a co-annular gaseous flow [27-28]. Care was taken to maintain traceability to previous simple round jet results in the limit as the annular flow went to zero. Facility capabilities limited early results to low gas-to-liquid velocity ratios not representative of liquid rocket injectors. Preliminary results after facility modifications at high velocity ratios indicated that the effect of acoustic waves is to impose sinusoidal structures onto the jet, but the effect seemed to depend in a complex way on pressure, velocity ratio, and on internal heat transfer inside the coaxial passages. Because density depends strongly on temperature in the vicinity of the critical pressure, it was determined that very accurate initial temperature measurements were required. Preparations to measure these temperatures to within 1 K were underway at the conclusion of this project. These measurements are planned to be performed in a follow-on project.

A small portion of this project was devoted to a separate effort to investigate detonations of subcritical liquid oxygen sprays in gaseous hydrogen [29-31]. The motivation was potential application in a pulsed detonation upper stage rocket engine. An experiment was conducted to understand the effect of gas-to-liquid oxygen ratio on wave speeds and post-detonation pressures. An analytical model of the constant volume limit of pulsed propulsion was also developed during the course of this research [29]. In the process of conducting the experiment, a great deal was also learned about instrumentation, ignition, and control approaches that could simultaneously survive cryogenic temperatures and withstand detonations. Reference detonations with room temperature gaseous hydrogen and gaseous oxygen produced classical Chapman-Jouget (CJ) detonations. Detonations with identical mass loadings of hydrogen and oxygen but with oxygen in a liquid phase produced significantly larger wave speeds and post-pressures than predicted by CJ theory. Computations were performed to show that the reason could be attributed to radial stratifications of oxygen concentrations caused by the coaxial injector used in the experiment.

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